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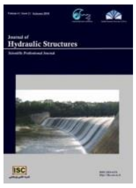

Using PAT for Energy Recovery and Pressure Reduction in Water Distribution Networks

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Abstract

Leakage is one of the main problems of urban water distribution networks. Leakage control and management can play an important role in increasing network efficiency and reducing water loss. Pressure reduction in water distribution networks is usually done using Pressure reducing valve (PRV), while the energy dissipated from head loss can be recovered to generate hydropower. In this study, the possibility of using pump as turbines (PATs) instead of PRVs in a water distribution network has been investigated. Regarding this purpose, the genetic algorithm is used by MATLAB software, in which the hydraulic model of the water distribution network is carried out in WaterGEMS software. At first, the aim of optimization is to determine the optimum output of PRVs. Then after replacing the PRVs with the PATs, the optimal curve for the PATs can be determined. Results show that the use of PATs to control the pressure is effective, so that compared to the basic model, the leakage rate has decreased by about 33% and the Nodal Pressure Reliability Index (NPRI) has increased by 0.41. Moreover, the nodal pressures have been significantly reduced, and the average pressure of the network decreased by 58%.

Keywords: Leakage; Water Distribution Networks; PRVs; PATs; Genetic Algorithm.

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1. Introduction

Water leakage is a common problem in many aging urban water networks. A worldwide average of 45 to 88 million cubic meters of water is lost during every day due to leaks in Water Distribution Networks (WDNs) [1]. In leakage management studies, pressure management is the simplest, fastest, and most economical method to reduce leakage. The control of pressure is one of the primary concerns in water distribution networks. High pressure values increase both leakage and risk of pipe damage, while low pressure may reduce water supply for consumers. As

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a result, excess pressure on systems must be reduced to standard range. Utilization of a Pressure Reducing Valve (PRV) to maintain standard pressures has been a common way for this purpose [2]. A PAT can be used instead of a PRV to produce hydropower energy and to control pressure. The use of renewable energy is increasing due to concerns about climate change and global warming. One of the renewable energies is hydropower, which derives energy from falling or running water which can be harnessed for useful purposes [3]. Micro Hydro Power (MHP) is another branch of hydropower; its capacity differentiates it from other branches. The application of MHP is in the class of small-scale hydropower projects. Pump as turbine (PAT) is one of the (MHP) projects that can be use instead of a Pressure Reduce Valve (PRV) in water distribution networks [4].

Due to the dynamic action of the fluid flowing through rotating elements, energy is continuously transferred in turbo machinery. Therefore, it is possible for the turbomachines to be used in reverse. A PAT is a turbine that works in a way similar to pumps [5]. In this mechanical device, water flow is used to generate electricity instead of energy to boost water flow. As a PAT works similarly to a regular pump, its implementation in the network does not require numerous modifications. Additionally, PATs' maintenance operations do not require specially trained personnel. The advantages of PATs utilization in water networks have been evaluated in various studies. The results have shown that PATs can be a reasonable alternative in a water distribution network. Fecarotta et, al [6] investigated the feasibility of hydropower potential in a water distribution network. The research results demonstrated that the installation of hydropower can produce interesting economic benefits. Morani et, al [7] introduced a novel mixed integer non-linear approach to find the optimal locations of both pressure reducing valves and pumps as turbines. The results showed that the proposed model can lead to good solutions, in term of energy and water saving purposes. Fontana et, al [8] investigated and analyzed various layouts for the installation of PATs in water distribution networks. They presented the procedure to determine the most appropriate and effective installation layout respect to different head and flow patterns. Pillay et, al [9] investigated the feasibility analysis of recovering energy in water distributions networks using PATs. They applied EPANET software to determine the strategic adjustment of PATs in water distribution networks. This study investigates the possibility of replacing PRVs with PATs using in a real water distribution network. Fernández García et, al [10] determined the optimal location and number of PATs in an irrigation network. They tried to maximize the amount of energy recovered by installation of PATs. The results showed that by using PATs, in addition to recovering energy, a significant amount of Co2 emissions can be saved. Stefanizzi et, al [11] presented an optimal strategy for hydraulic energy harvesting in water distribution networks by installing PATs. They proposed two new approaches for PAT selection according to maximum available energy, average flow rate and maximum energy recovery. Results showed that over 3.5 MWh per day was achieved by utilizing PATs.

In the present study, the feasibility of using PATs for pressure control in water distribution networks is investigated. Using WaterGems software, the Baharan network located in Sanandaj city in Iran is simulated. For this purpose, three scenarios have been defined to compare and evaluate the effect of PRVs and PATs on leakage reduction, pressure control and recovering energy.

2. Case study and methodology

For the purpose of evaluating the effectiveness of the suggested method and the importance of applying PRVs and PATs in controlling pressure (minimizing leakage) and producing energy, the proposed method has been exerted to a water distribution network. It is called the Baharan network, located in the city of Sanandaj, Iran. The city is located in the foothills of the Zagros Mountains. As it is restricted by mountains, the city contains large height differences. The Baharan network is located in northwest Sanandaj which is supported by a reservoir that located 1,541 meters above sea level. The elevation changes between 1,430 and 1,1488 meters above sea level. The high-altitude difference observed causes the city's WDN to be under high pressure as a result of gravity. The water distribution system consists of 121 pipes and 113 nodes. The pipes are made of asbestos cement, cast iron, ductile iron and polyethylene with diameters between 63 and 500 mm. The water distribution network has been divided into four District Metered Areas (DMAs). dividing a water distribution network into DMAs can be assumed as one of the most efficient and cost-effective methods of optimizing the performance of a water distribution network in terms of reducing the real water loss rates [12]. Segmenting the network has been accomplished by installing isolation valves in pipes that define DMA boundaries. A PRV or PAT can only be installed in pipes that supply water to one or more DMAs. Figure 1 shows the Baharan WDN. The elevations of the network nodes have also been demonstrated in Figure 2.

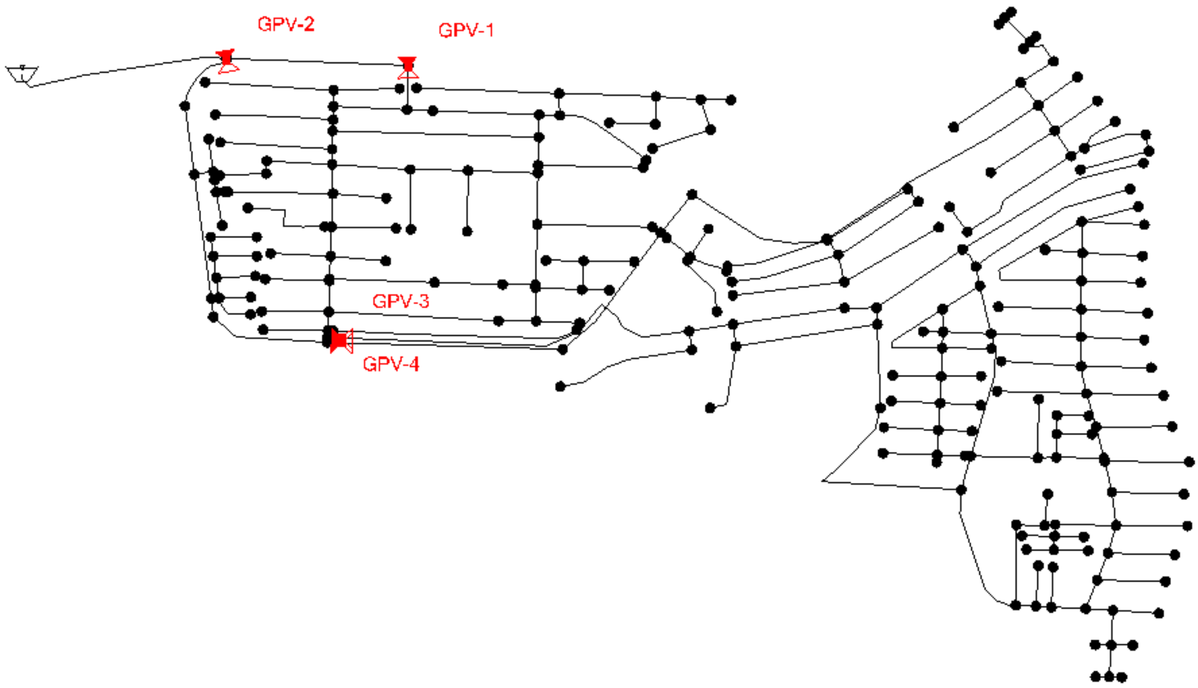

Figure 1. The Baharan layout of water distribution network

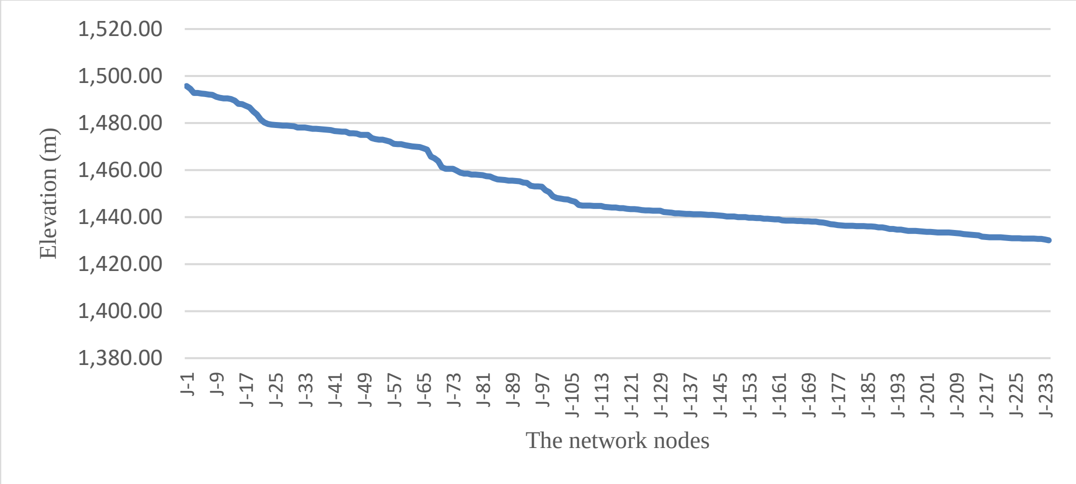

Figure 2. The elevation of the network nodes

Three scenarios were developed for comparing PRV and PAT implementations in the Baharan water distribution network. All the scenarios happened on the same pressure zones. In scenario 1, no PRVs or PATs are placed in the entrance of pressure zones. In scenario 2, PRVs are placed in the entrance of pressure zones for the PRVs performance a pattern is defined for different times. In scenario 3, the PRVs are being replaced by PATs, in exact same point where the PRVs were installed in previous scenarios. WaterGEMS software was used to evaluate each scenario separately, and results were compared. There are two explanations of numerical water distribution system modeling including steady-state analysis and extended period analysis [13,14]. In case of extended period analysis, computations are performed over an extended time period at variables water consumption and system operating conditions [15]. In the present study, the extended period analysis has been applied to the Baharan WDN. The population density of the study area is 321 people per hectare, and the consumption of water is considered to be 200 liters per capita per day (LPCD). Figure 3 shows the demand pattern considered for the simulation. The consumption coefficient has been determined according to hourly fluctuations in water consumption levels during day and night.

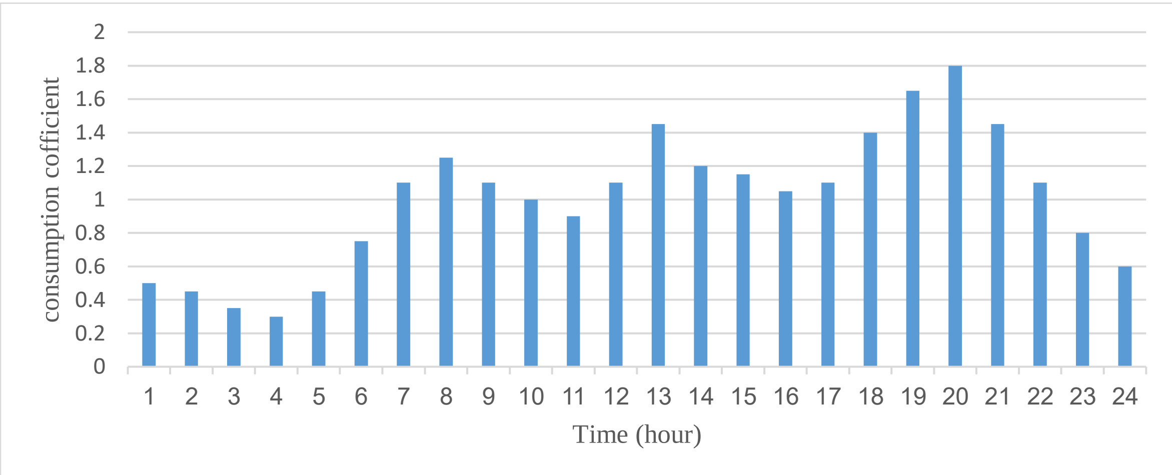

Figure 3 The demand pattern of the case study

3. Hydraulic modeling

The present study proposed a procedure to choose and define the optimum scheduling for PATs and PRVs separately, in order to maximize network node pressure reliability and minimize network leakage. The metaheuristic algorithm GA is utilized to maximize the benefits of network node pressure reliability and leakage reduction. The objective function used to evaluate network reliability is as follows:

$$NPRI(j,t) = \begin{cases} 0, & p < 10 \\ \frac{1}{32}(p-10), & 10 < p < 26 \\ \frac{1}{10}(p-26)+0.5, & 26 < p < 31 \\ 1 & p = 31 \\ -\frac{1}{38}(p-31)+1, & 31 < p < 50 \\ -\frac{1}{40}(p-50)+0.5, & 50 < p < 60 \\ 0.25, & 60 < p \end{cases} \tag{1}$$

where NPRI (j,t) is the value of the Nodal Pressure Reliability Index at node j and time t which is utilized to evaluate the reliability of WDN. p refers to nodal pressure in node j respect to time t. The network nodal pressure index of reliability is obtained from relation 2 [16]:

$$NPRI = \frac{\sum_{j=1}^{NN} Q_{j,t}^{req}(NPRI(j,t))}{\sum_{j=1}^{NN} Q_{j,t}^{req}} \tag{2}$$

where NPRI is the index of network nodal pressure reliability, NN is number of junctions in network, and $Q_{j,t}^{req}$ refers to water demand in junction j at time t. The following equations have also been used to calculate leakage of WDN and the amount of energy recovered by PATs [17]:

$$Q_l = cp^n \tag{3}$$

Where *p* is pressure head, *Q* is leakage flow rate, *c* refers to the coefficient of leakage, and *n* is leakage exponent. The *n* parameter can take values between 0.5 and 2.5, depending on WDN conditions such as leak hydraulics, soil properties, behavior of pipe material, and water demand. In the present paper, due to the conditions of the studied network, the *n* exponent has been considered equal 1.15. The turbine production power can be determined as following equation [18]:

$$P_{output} = \eta \rho g H Q \tag{4}$$

Where the flow rate *Q* and head *H* can be calculated from the site while density ρ, the turbine efficiency η and acceleration due to gravity *g* are constants.

4. Optimization Algorithm

In optimization problems, the Genetic Algorithm (GA) is one of the most popular optimization algorithms. It is a search heuristic algorithm which is inspired by the biological evolution process. the algorithm deals with the definition of problem variables as binary strings identified as genes. A set of genes forms a chromosome which can be considered as one of the possible solutions of the optimization problem. The process is continued until the search tends to an optimal solution. At first in the GA, randomly created primary populations of chromosomes are generated. Then the objective function is employed to find the fitness of each chromosome. The chromosomes with the better fitness amongst the population can be obtained by the selected operator. By use of mutation and crossover operators, a new population is generated. The iterative loops should be performed till the termination criterion is met [19]. The GA is being widely utilized to deal with WDN problems, including optimal network design pump scheduling and network calibration [20-23]. In this paper, the genetic algorithm is utilized for optimal setting of PRVs and PATs to maximize the network nodal pressure reliability index (NPRI), and minimize leakage in a WDN. It is to be mentioned that the pressure in each node should not overstep the corresponding standard pressure. In WaterGEMS, the Darwin Designer is applied for optimization purposes using the GA. It can enable designers to optimize either a whole WDN or a portion of it. The parameters of the GA are utilized to control the underlying algorithm used in the process of optimization [24].

5. Results and Discussion

The simplest, fastest, and most economical way to reduce leakage is to manage pressure value in water distribution networks. In the present study, the possibility of using pump as turbines (PATs) instead of pressure reducing valves (PRVs) has been investigated. For this purpose, the results of each scenario have been presented in low, medium and maximum consumption hours, and the results have been compared with each other. The results of each scenario have been presented in Table 1. Besides, figure 4 shows the nodal consumption discharge with and without PATs installation.

Table 1. Leakage and nodal reliability index (NPRI) for each scenario

	Scenario1		Scenario2		Scenario3	
Time	Leakage (L/s)	NPRI	Leakage (L/s)	NPRI	Leakage (L/s)	NPRI
4 A.M	56.64	0.28	39.42	0.7	35.22	0.67
10 A.M	56.22	0.28	40.68	0.67	37.59	0.71
8 P.M	55.32	0.3	44.07	0.67	41.22	0.69

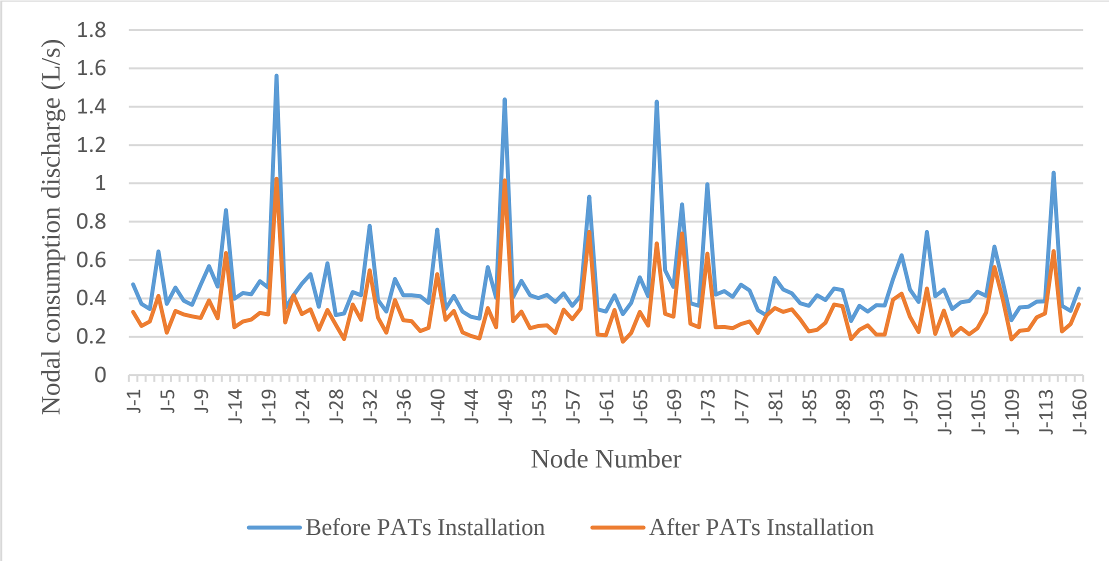

Figure 4. Nodal consumption discharge with and without PATs

According to Table 1, the amount of leakage in scenario 2 decreased by 26% compared to the scenario 1, and the NPRI increased by an average of 0.39. Moreover, in scenario 3, the leakage decreased by 32% compared to the first scenario and the NPRI value increased by 0.41. Figure 5 shows the amount of pressure in scenarios 1 to 3 at maximum consumption hours.

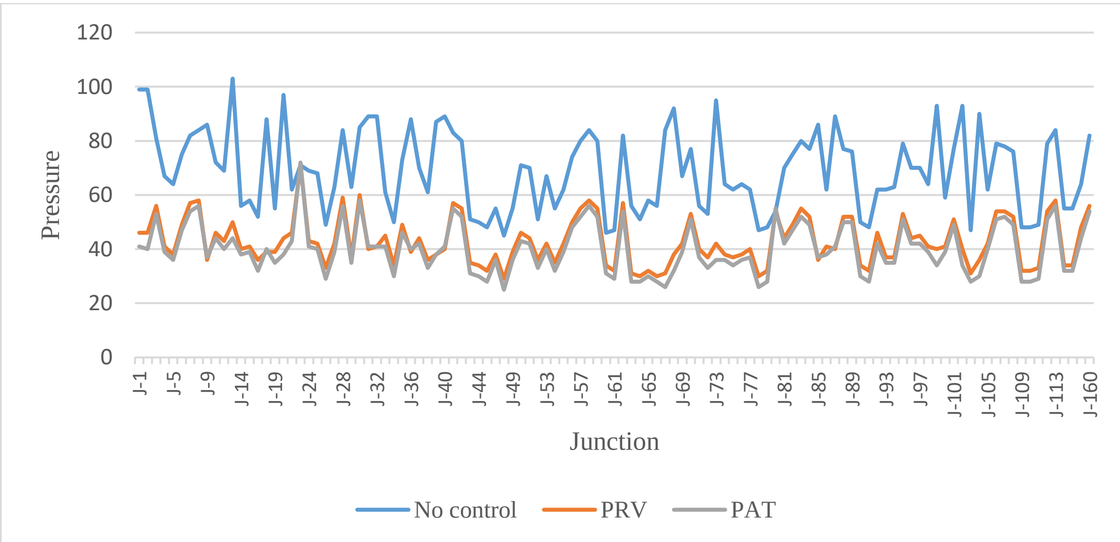

Figure 5. The junction pressure values at maximum consumption hours

According to the figure 5, the use of PATs instead of PRVs has a significant effect in controlling and reducing the pressure in the WDN. Figure 6 to 9 show the production power of the PATs in 24 hours. Moreover, the annual recovered energy of each PAT has been presented in table 2. As can be seen, the most energy produced in 24 hours belongs to peak consumption hours.

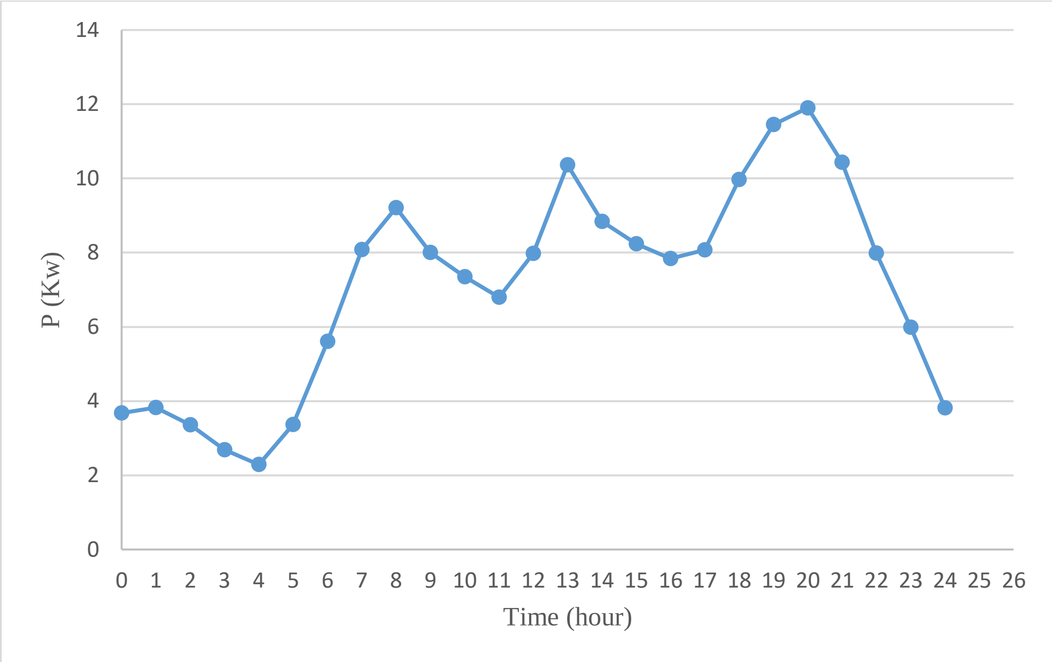

Figure 6. The production power of the PAT 1 in 24 hours

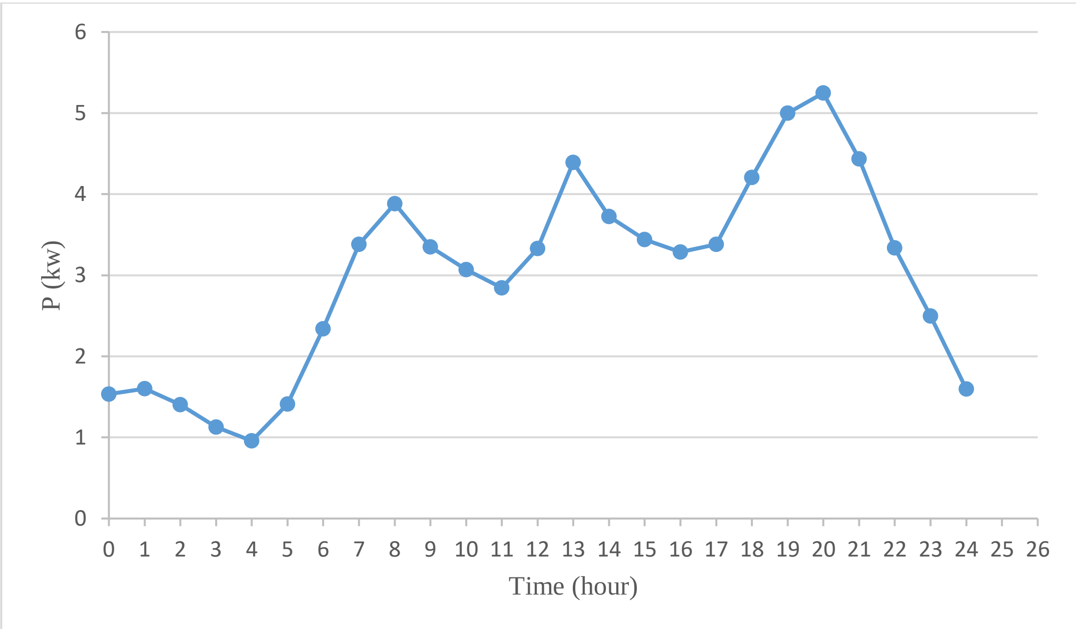

Figure 7. The production power of the PAT 2 in 24 hours

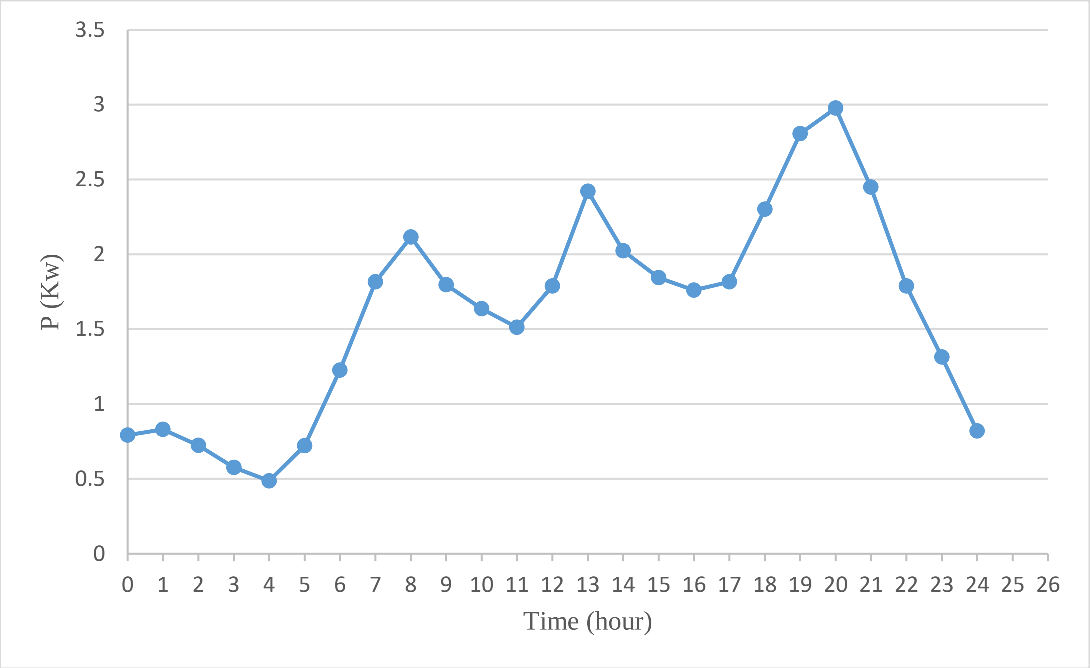

Figure 8. The production power of the PAT 3 in 24 hours

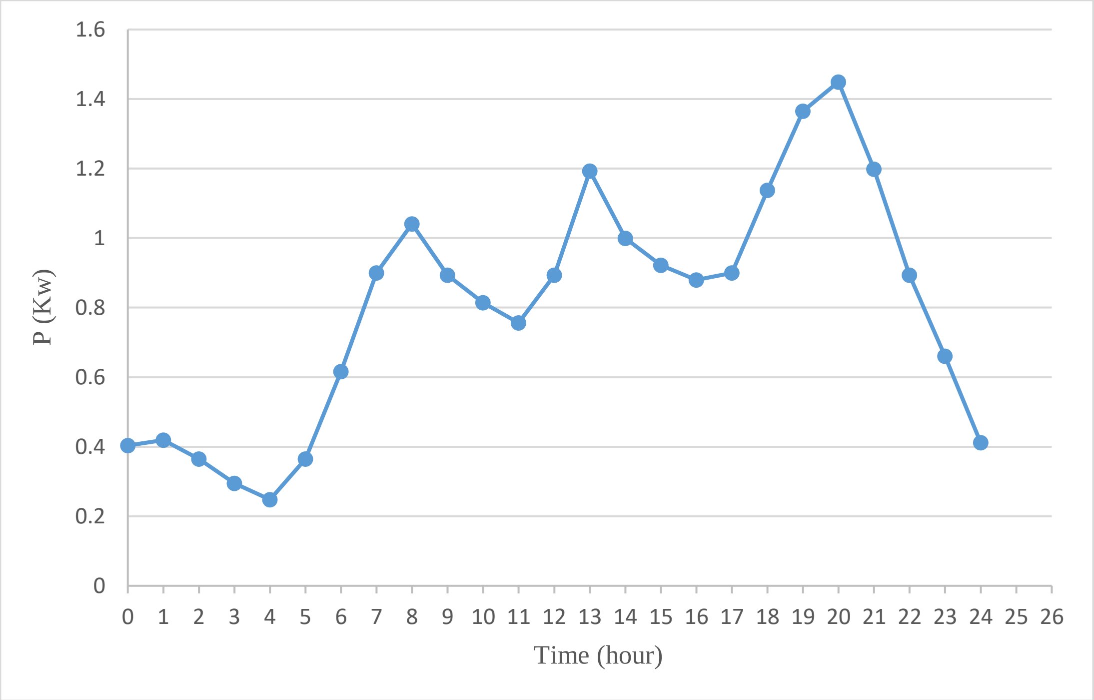

Figure 9. The production power of the PAT 4 in 24 hours

Table 2. The annual recovered energy of each PAT

PAT number	Annually recovered energy (Kwh)
1	87,472
2	78,951
3	70,882
4	35,071

A comparison of each scenario for leakage reduction and producing energy has been presented in table 3.

Table 3. The comparison of each scenario for annual saved water and energy

	Scenarios		
	No control	PRV	PAT
Annual saved water (m^3)	-	462,633.12	569,224.8
Total annually recovered energy (Kwh)	-	-	272,376

As can be seen in Table 3, despite the better control of leakage in scenario 3 than scenario 2, a significant amount of hydropower has been generated in scenario 3. In order to evaluate the economic feasibility of the project, the cost and benefit of the project can be considered. Eventually the economic feasibility demonstrates that pressure management by PATs is an effective method because while reducing leakage, considerable hydropower energy is also produced.

6. conclusions

Pressure management is one of the most efficient and cost-effective ways to reduce leakage in WDNs. Due to the direct relationship between leakage and pressure in WDNs, it is possible to control the amount of leakage in the network with proper pressure management. As a common approach, pressure reduction in water distribution networks is usually done using PRVs, while it can be beneficial that the energy dissipated from head loss is recovered to generate hydropower. In this paper, the feasibility of using PATs in pressure control for the Baharan network located in Sanandaj city in Iran, was investigated. For this purpose, three scenarios were defined to compare and evaluate the effect of PRVs and PATs on NPRI and the reduction in network leakage. At first in scenario 1, the model was evaluated without any PRV, and the pressure in the nodes was examined. Results showed that the pressure in the nodes was very high. In scenario 2, in order to control the additional pressure in the nodes, four PRVs were placed at the entrance of each pressure zone. Finally, in scenario 3, PATs were placed instead of the PRVs. Comparing the results in different scenarios showed that the pressure control by PATs while reducing the amount of leakage more than the PRVs, produces a significant amount of hydropower energy. The network's NPRI in scenario 3 compared to scenario 1 has increased by about 0.41, and the leakage rate has decreased by about 33 percent. By using PATs, the nodal pressures have been significantly reduced, and the average pressure of the network decreased by 58 percent that was within the allowed range. In addition, the amount of hydropower produced by PATs was about 272,376 (KWh/year). According to the results of this study, the use of PATs can be a good alternative in water distribution networks, especially in mountainous regions or areas with high altitude differences.

References

1. Corcoran, L., McNabola, A. and Coughlan, P., 2016. Optimization of water distribution networks for combined hydropower energy recovery and leakage reduction. Journal of Water Resources Planning and Management, 142(2), p.04015045.
2. Jones, F.T. and Barkdoll, B.D., 2022. Viability of Pressure-Reducing Valves for Leak Reduction in Water Distribution Systems. Water Conservation Science and Engineering, 7(4), pp.657-670.
3. Binama, M., Su, W.T., Li, X.B., Li, F.C., Wei, X.Z. and An, S., 2017. Investigation on pump as turbine (PAT) technical aspects for micro hydropower schemes: A state-of-the-art review. Renewable and Sustainable Energy Reviews, 79, pp.148-179.
4. Novara, D. and McNabola, A., 2021. Design and year-long performance evaluation of a pump as turbine (Pat) pico-hydropower energy recovery device in a water network. Water, 13(21), p.3014.
5. Lima, G.M., Junior, E.L. and Brentan, B.M., 2017. Selection of pumps as turbines substituting pressure reducing valves. Procedia Engineering, 186, pp.676-683.
6. Fecarotta, O., Aricò, C., Carravetta, A., Martino, R. and Ramos, H.M., 2015. Hydropower potential in water distribution networks: Pressure control by PATs. Water resources management, 29, pp.699-714.
7. Morani, M.C., Carravetta, A., D’Ambrosio, C. and Fecarotta, O., 2021. A new mixed integer non-linear programming model for optimal PAT and PRV location in water distribution networks. Urban Water Journal, 18(6), pp.394-409.
8. Fontana, N., Marini, G. and Creaco, E., 2021. Comparison of PAT installation layouts for energy recovery from water distribution networks. Journal of Water Resources Planning and Management, 147(12), p.04021083.
9. Pillay, E., Kumarasamy, M., Adu, J., Thirumuruganandham, S.P., Paruk, A. and Naidoo, M., 2022. Feasibility analysis of energy recovery using PATs in water distribution networks. Water, 14(7), p.1150.
10. Fernández García, I., Perea, R.G. and Rodríguez Díaz, J.A., 2022. New model for determining optimal PAT locations: maximizing energy recovery in irrigation networks. Journal of Water Resources Planning and Management, 148(11), p.04022054.
11. Stefanizzi, M., Filannino, D., Capurso, T., Camporeale, S.M. and Torresi, M., 2023. Optimal hydraulic energy harvesting strategy for PaT installation in Water Distribution Networks. Applied Energy, 344, p.121246.
12. Kowalska, B., Suchorab, P. and Kowalski, D., 2022. Division of district metered areas (DMAs) in a part of water supply network using WaterGEMS (Bentley) software: a case study. Applied Water Science, 12(7), p.166.
13. EKWULE, O. and UTSEV, J., 2019. Evaluation of a Municipal Water Distribution Network Using waterCAD and waterGEMS. Kastamonu University Journal of Engineering and Sciences, 5(2), pp.147-156.

14. Shang, F., Rossman, L.A. and Uber, J.G., 2023. EPANET-MSX 2.0 user manual. EPA/600/R-22/199. Cincinnati: USEPA.
15. Arandia, E. and Eck, B.J., 2018. An R package for EPANET simulations. Environmental modelling & software, 107, pp.59-63.
16. Dini, M., Mohammadikaleibar, A., Hashemi, S. and Nourani, V., 2022. Stochastic long-term reliability of water distribution networks using Monte Carlo simulation. Urban Water Journal, 19(2), pp.151-160.
17. Muranho, J., Ferreira, A., Sousa, J., Gomes, A. and Marques, A.S., 2014. Pressure-dependent demand and leakage modelling with an EPANET extension–WaterNetGen. Procedia Engineering, 89, pp.632-639.
18. Kaunda, C.S., Kimambo, C.Z. and Nielsen, T.K., 2014. A technical discussion on microhydropower technology and its turbines. Renewable and Sustainable Energy Reviews, 35, pp.445-459.
19. Mirjalili, S. and Mirjalili, S., 2019. Genetic algorithm. Evolutionary Algorithms and Neural Networks: Theory and Applications, pp.43-55.
20. Jafari, R., Khanjani, M.J. and Esmaeilian, H.R., 2015. Pressure management and electric power production using pumps as turbines. Journal-American Water Works Association, 107(7), pp.E351-E363.
21. Do, N.C., Simpson, A.R., Deuerlein, J.W. and Piller, O., 2016. Calibration of water demand multipliers in water distribution systems using genetic algorithms. Journal of water resources planning and management, 142(11), p.04016044.
22. Cimorelli, L., D'Aniello, A. and Cozzolino, L., 2020. Boosting genetic algorithm performance in pump scheduling problems with a novel decision-variable representation. Journal of Water Resources Planning and Management, 146(5), p.04020023.
23. Du, B., Zha, D., Guo, J. and Yu, X., 2023. Optimization of pump scheduling in waterworks considering load balancing using improved genetic algorithm. Journal of Intelligent & Fuzzy Systems, (Preprint), pp.1-19.
24. Świtnicka, K., Suchorab, P. and Kowalska, B., 2017. The optimisation of a water distribution system using Bentley WaterGEMS software. In ITM Web of Conferences (Vol. 15, p. 03009). EDP Sciences.